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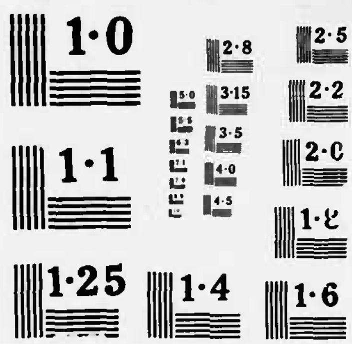
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# PROTON BACKSCATTERING IN BULK SILICON AT LARGE ANGLES OF INCIDENCE

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A. H. Hoffland
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T. R. Locker

AIR FORCE WEAPONS LABORATORY

December 1988

Final Report

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AIR FORCE WEAPONS LABORATORY
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This report describes proton backscatter studies performed by at the ~~Air~~ Force Weapons Laboratory (AFWL) personnel at the Los Alamos National Laboratory (LANL) Tandem Van de Graaff Accelerator Facility. The objective ~~of this work~~, was to determine if backscattering protons were sufficient to alter the radiation induced proton damage in silicon electronics when high energy protons (6 MeV and below) bombarded bulk silicon at large angles of incidence (>65 deg). The overall results showed that when the angles of incidence of bombarding protons (on bulk silicon) approached 80 deg, and their energies were lowered to ≈100 KeV about the number of backscattering protons approached 12 percent of the bombarding number. At this point (and at lower energies), the effect of the backscattering protons would become significant and they would have to be taken into account when determining the radiation induced proton damage in silicon electronics. The number of backscattering protons, their energies, and their angles of reflections (for silicon and other solids) can accurately be determined from a computer program called TRIM (Transport of Ions in Matter). Keywords:


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## PREFACE

The authors wish to acknowledge the invaluable technical support provided by the test personnel at the Los Alamos National Laboratory's (LANL) Tandem Van de Graaff Accelerator. We would like to give a special thanks to Larry Rowton of LANL for his guidance and support in the successful construction of the experimental setup. Finally, we would also like to recognize Dr David Holtkamp of LANL for his theoretical support and for introducing AFWL personnel to the TRIM computer program.

CONTENTS

# FIGURES

# 1.0 INTRODUCTION

Past research (Refs. 1, 2) has shown that when Metal-Oxide-Semiconductor (MOS) devices were irradiated with charged particles (protons and alpha particles), the ionizing radiation damage produced in the test samples was not only influenced by the applied electrical field across the gate oxide, but was also affected by the angle between the field and the incident particles (Fig. 1).

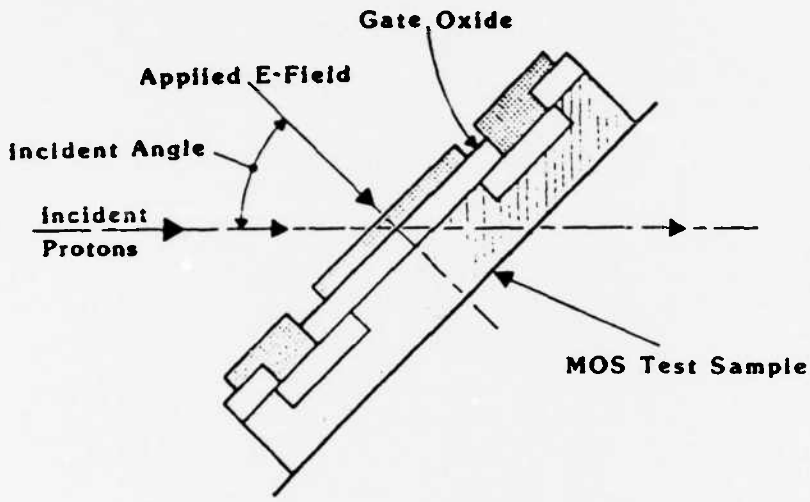


Figure 1. Illustration of a MOS device being bombarded by protons at an incident angle >0.

The investigations also showed that this angular dependency could be explained by the "columnar recombination model" (Ref. 3). This model predicts that the ionizing radiation damage generated in a biased MOS structure from charged particles (such as protons), is proportional to the angle between the gate oxide field and the incident particles. This said, the maximum damage would occur when the tracks of the incoming particles are at 90 deg with respect to the oxide field, and the minimum damage would occur when the particle tracks are parallel to the field.

A possible discrepancy arose in the above explanation when recent Air Force Weapons Laboratory (AFWL) data (Ref. 4) suggested that the ionizing radiation damage, induced by high energy protons in biased MOS devices, was not always proportional to the angle of the incident particles. A sample of this conflicting data is presented in Fig. 2.

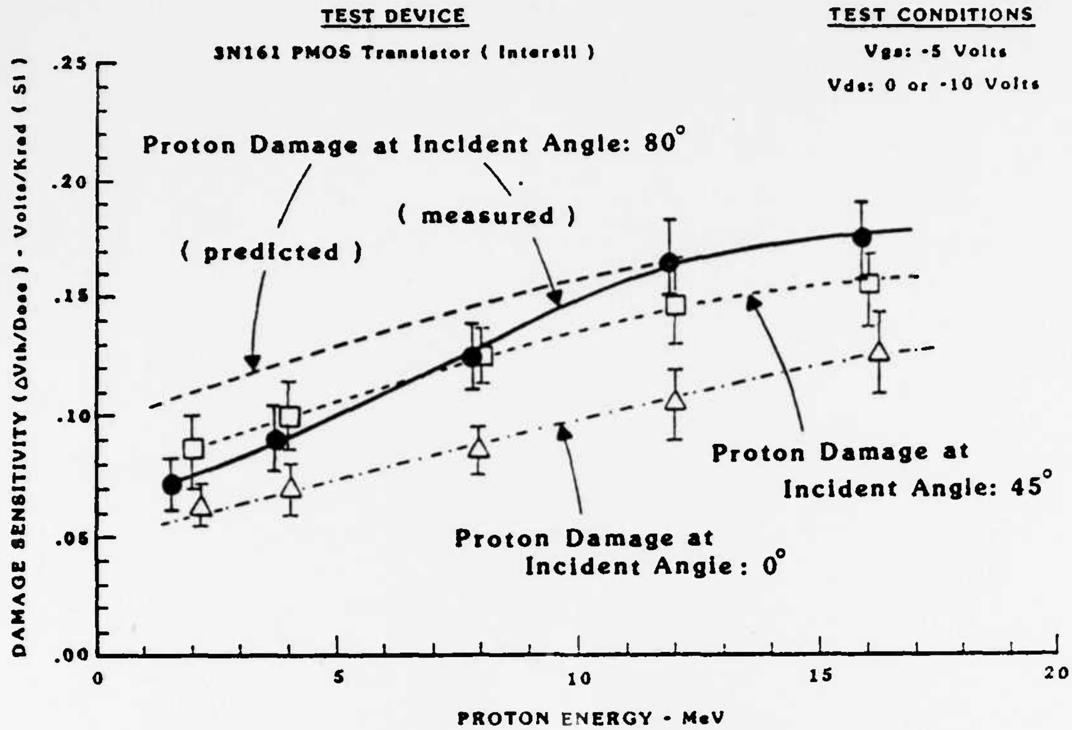


Figure 2. PMOS data: comparison of damage sensitivity, ΔVth/dose, between 2 to 16 MeV protons, at three different angles of incidence, for a Vgs of -5 V.

Plotted above, as a function of proton energy, is the damage sensitivity in change in gate threshold voltage per dose (ΔVth/dose) for five different energy protons striking test samples at 0, 45, and 80 deg angles of incidence. The data from the 0 and 45 deg incident protons agreed with the theoretical model. That is, under the influence of an applied gate field, the radiation damage increased as the incident angle expanded from 0 to 45 deg. However, the measured data from the 80 deg protons deviated from the predicted response. At this incident angle, the damage sensitivity dropped significantly below the predicted level when the proton energy decreased below 12 MeV. Below 6 MeV, the 80 deg protons produced less damage than the protons at 45 deg. The columnar recombination model predicts that this excessive drop should not have occurred.

A possible explanation for this discrepancy was that many of the 80 deg incident protons were not travelling completely through the silicon test samples. A high percentage were deflecting off the sample surfaces, especially as the energy of the incoming proton was decreased. The work presented in this report will attempt to verify or disprove this backscatter concept.

# 2.0 APPROACH

## 2.1 EXPERIMENTAL

The objective of this investigation was to determine if backscattering becomes significant when high energy protons (6 MeV or less) bombard bulk silicon at large angles of incidence (>65 deg). To accomplish this task, silicon wafers were irradiated with high energy protons (6, 4, and 2 MeV) at various incident angles. During the irradiations, a sensitive Faraday cup was rotated in small increments around the sample to detect protons (positive currents) coming out of the wafer. The setup for these scatter measurements is illustrated in Fig. 3.

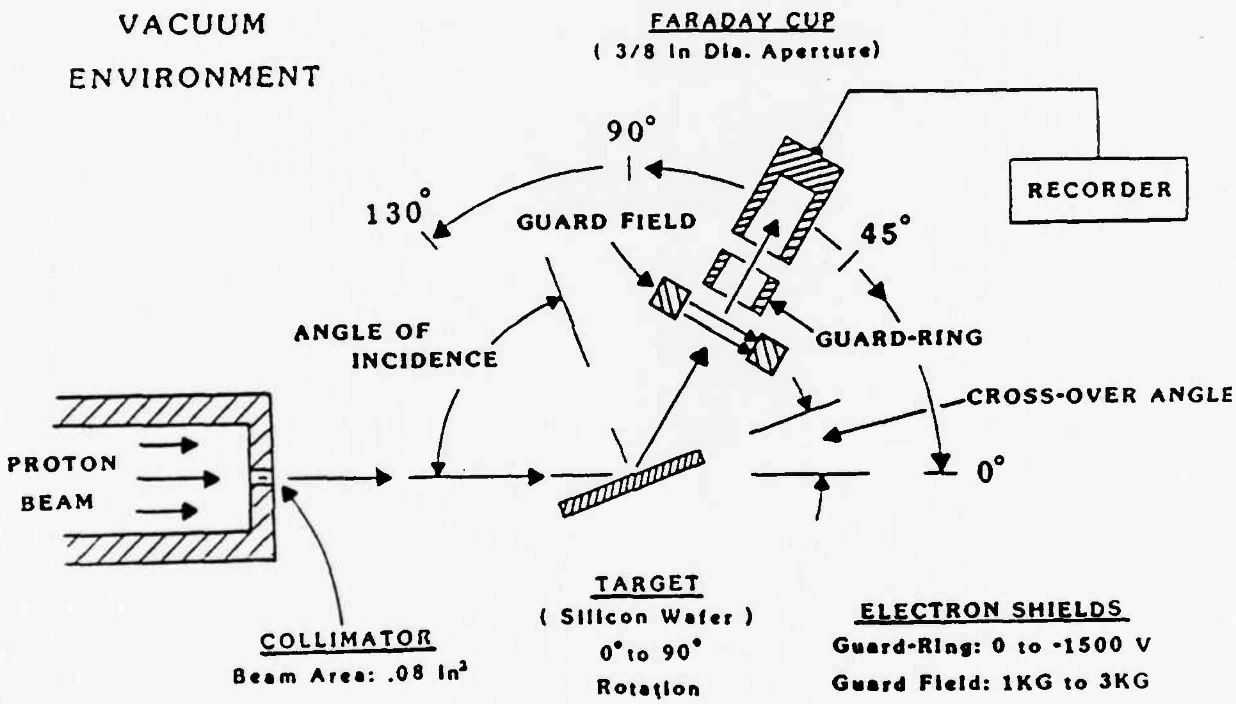


Figure 3. Proton scatter test setup.

The test environment was provided by the Los Alamos National Laboratory's (LANL) Tandem Van de Graaff accelerator facility. In the setup, monoenergetic protons are shown striking a silicon target through an adjustable collimator. The desired angle of incidence was obtained by prepositioning the target (a 546-$\mu$m-thick silicon wafer) through a remote manipulator. In addition to providing zero to 90 deg rotation, the manipulator also allowed the target to be moved in and out of the radiation beam.

To prevent the "masking" of the backscattering protons by the more numerous backscattering electrons, two electron shields (guarding the entrance to the Faraday cup) were employed. This combination of both shields generated an electrical and a magnetic field strong enough to prevent scattering electrons from entering (or leaving) the Faraday cup. However, at the same time, the two fields were not strong enough to repel the heavier protons. In the actual tests, both shields moved in sync with the Faraday cup.

Limitations in the experimental setup were in the following areas: (1) incident beam energies, (2) detection sensitivity, (3) accuracy of backscatter angle measurements, and (4) assessment of the total number of backscattering protons.

The first limitation was caused by the test facility itself. For the required steady beam currents, the LANL accelerator was limited to a minimum proton energy of 2 MeV. Below this energy (in the KeV range), a stable beam current of the magnitude required could not be obtained. As a result, the experimental measurements had to be limited to incident protons of 2 MeV and above.

The second limitation was in the sensitivity of the setup's detector system. Unlike a "charge particle detector", the sensitivity of the Faraday cup was limited by the resolution of the recorder (1.0 pA). This translates to a system that can only detect backscattering protons above the level of $6.0 \times 10^6$ particles/s. The recorder used in this setup was a Keithley 610C Electrometer.*

Resolution between the measured angles of reflection was also limited. Measuring accuracy of the proton backscatter angles of reflection was dependent upon the diameter of the Faraday cup opening and the distance between the cup's opening and the target. In the above setup, the diameter of the cup's opening was 1.0 cm, and the distance between the opening and the silicon target was 11.0 cm. With these two parameters, the angular deviation of the backscatter angle measurements was ±3 deg.

*Keithley Instruments, Inc., 28775 Aurora Road, Cleveland, Ohio 44139.

A fourth limitation was the inability to detect backscattered protons outside the viewing plane of the Faraday cup. This restriction was attributed to the cup's rotating apparatus within the setup's test chamber. Machinery inside the test chamber only allowed the cup to be moved in a two-dimensional plane. In reality, if protons are reflecting out of the target, they would be coming out in a three-dimensional plane. A consequence would be that some back-scattering protons may not be detected by the Faraday cup. The result would be a backscatter current measurement smaller than actual.

However, since the primary objective of this effort was to determine if proton backscattering (6 MeV and below) was significant, >10 percent of the incident number, it was determined that the setup was adequate for initial observations.

## 2.2 THEORETICAL

To add validity to the recorded test findings, computer calculations were performed to determine if the experimental results agree with an accepted theoretical model. The model used in this correlation was a Monte Carlo computer program called "TRIM" (Transport of Ions in Matter) (Refs. 5 and 6). This program, developed by the IBM Corporation, calculates the following: (1) the penetration of energetic ions into solids, (2) the final distribution of the ions and kinetic phenomena associated with the ion's energies losses (target damage, ionization and phonon production), and (3) all backscattered ions with this energies and angles of emission.

It was the number of backscattering ions emerging from a target, their energies, and the angles of emission that was of interest in this work. Specifically, theoretical calculations of backscatter protons as a function of 6, 4, and 2 MeV protons bombarding a silicon target at large angles of incidence (>65 deg) were compiled. From the data, a comparison was made between the experimental and the theoretical results. The plan was that if there was agreement between the measured and the theoretical, then the TRIM calculations would be extended (if needed) to a wider range of energies to answer the question set forth in the objective.

## 3.0 EXPERIMENTAL RESULTS

Summaries of the measured results are presented in Figs 4 to 8. All of the plots illustrate the surface backscatter current (electrons or protons) generated from high energy protons bombarding a silicon wafer at a selected angle of incidence. Specifically, the backscatter currents (measured with a Faraday cup) are plotted as a function of the angular position of the measuring cup with respect to the target (Fig. 3).

Figure 4 shows the case when the magnetic guard field is removed from the measuring setup. With 155 to 165 nA of 4 MeV proton beam current bombarding the silicon target at an 80 deg angle of incidence, the backscatter current count indicated only electrons (negative currents) were scattering off the target. No backscattering protons (positive current) were detected. Under this test condition, two data curves were plotted.

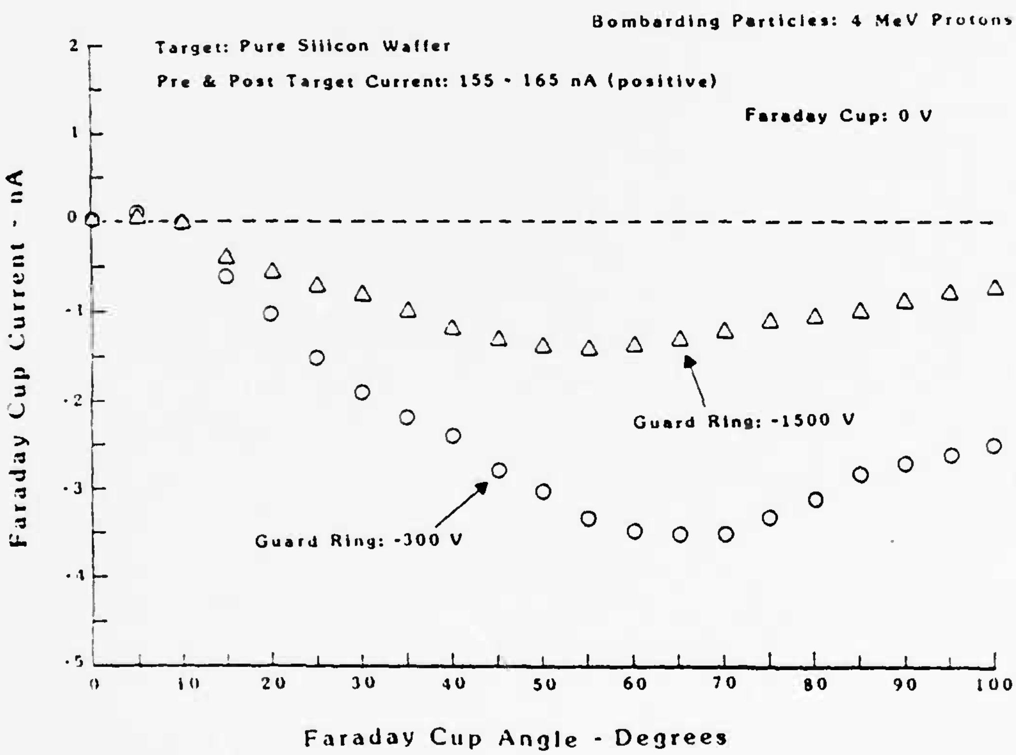


Figure 4. Backscattering electrons as a function of 4 MeV protons bombarding a silicon target at 80 deg angle of incidence.

The first group of data points was recorded with a guard ring potential of -300 V. Under this condition, backscattering electrons with energies <300 eV were prevented from entering (or leaving) the Faraday cup. This data curve

shows that immense numbers of electrons, >300 eV, were scattering off the target at a large number of reflecting angles. The peak scatter number (≈-3.5 nA) was occurring at an angle of reflection between 50 and 60 deg (Faraday cup angle minus the cross-over angle).

The second collection of data points was recorded with a guard ring potential of -1500 V. This high electric field was chosen to reduce the large number of reflecting electrons (energies as high as 1.5 KeV) from entering the Faraday cup. This was done in hopes that the electron backscatter could would be low enough to allow the detection of possible backscattering protons. The plotted results showed that the electron backscatter count was significantly decreased, but not low enough to sense reflecting protons. A large number of backscattering electrons (>1.5 KeV) were still being detected by the Faraday cup.

Figures 5 to 8 present the results when both the magnetic and electrical guard fields were incorporated into the test setup. In all four data graphs, the backscattering electrons were basically eliminated from the measurements. The results were plots showing positive current counts, which indicated backscattering protons.

Figure 5 shows the plots of backscatter protons as a function of 125 to 135 nA of 6 eV protons bombarding a silicon target at 80 deg angle of incidence. The results show that there were a small number of protons coming out of the front surface of the target, with a peak positive current of 14.5 pA occurring at ≈6 angle of reflection. Analyzing this positive current from the Faraday cup crossover point to the 30 deg position, results in a backscatter count of <0.1 percent of the total incident number.

Backscattering protons as a function of 4.0 eV protons bombarding the silicon target at 80 deg angle of incidence are shown in Fig. 6. With the exception of slightly higher backscatter counts, the plots were approximately the same as those recorded in the 6.0 eV protons irradiation. The backscatter current at the 4.0 MeV level was ≈0.2 percent of the total incident current. This was roughly twice the percentage recorded at the 6 MeV level.

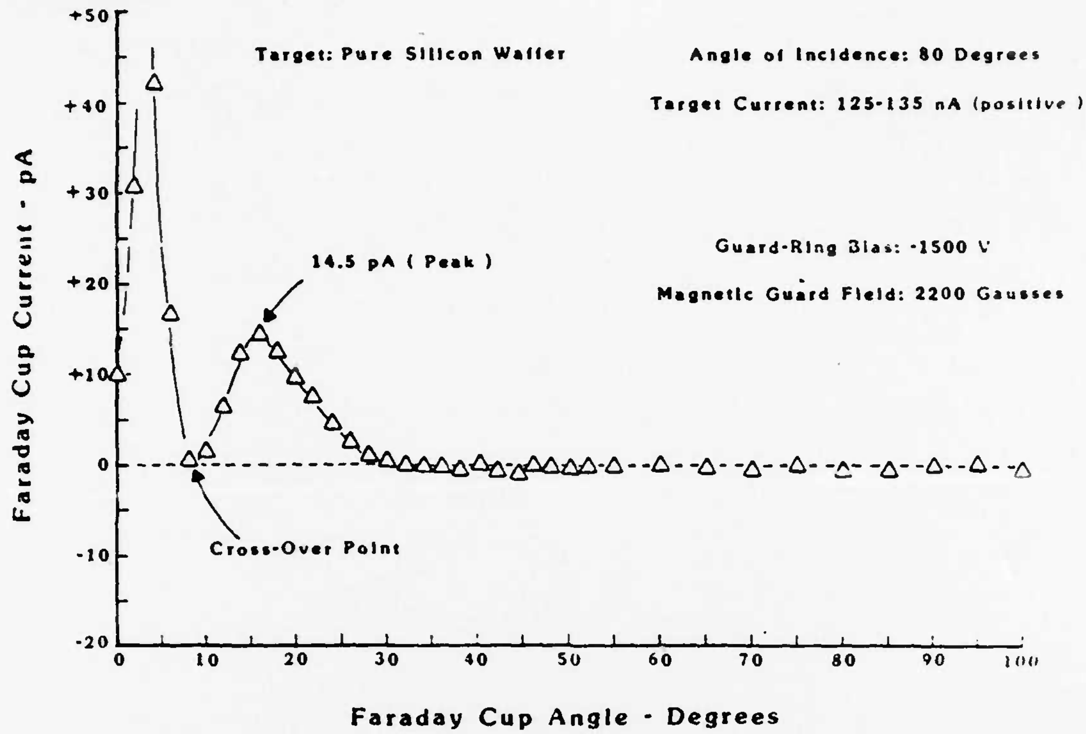


Figure 5. Backscatter protons as a function of 6 MeV protons bombarding a silicon target at 80 deg angles of incidence.

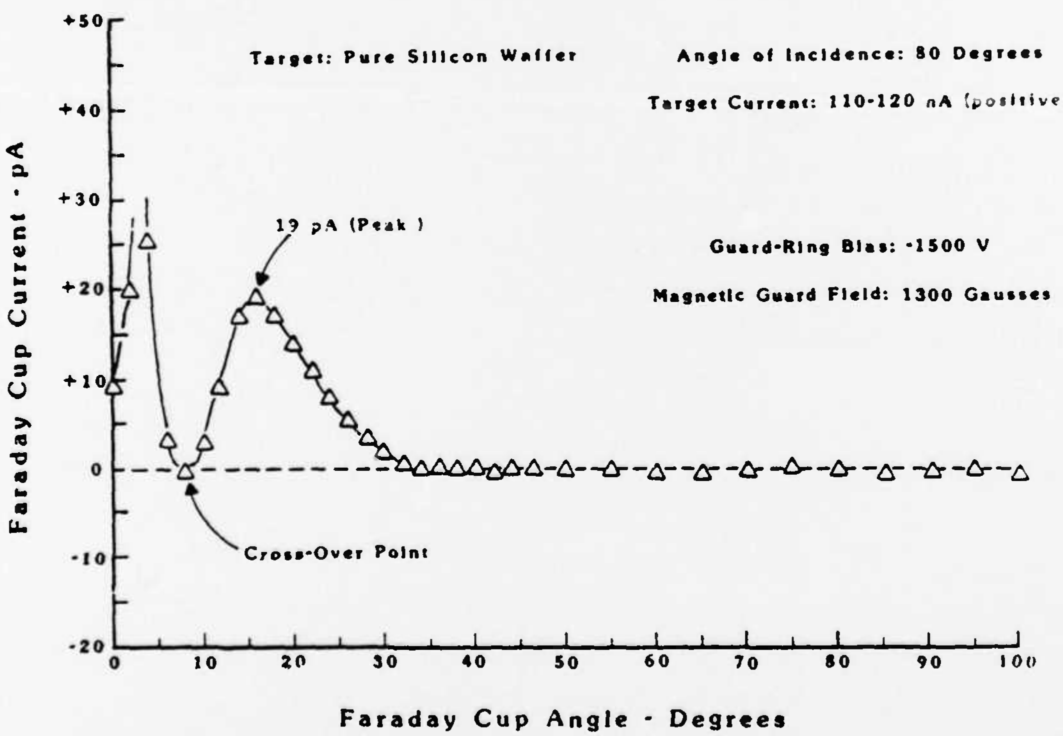


Figure 6. Backscatter protons as a function of 4 MeV protons bombarding a silicon target at 80 deg angle of incidence.

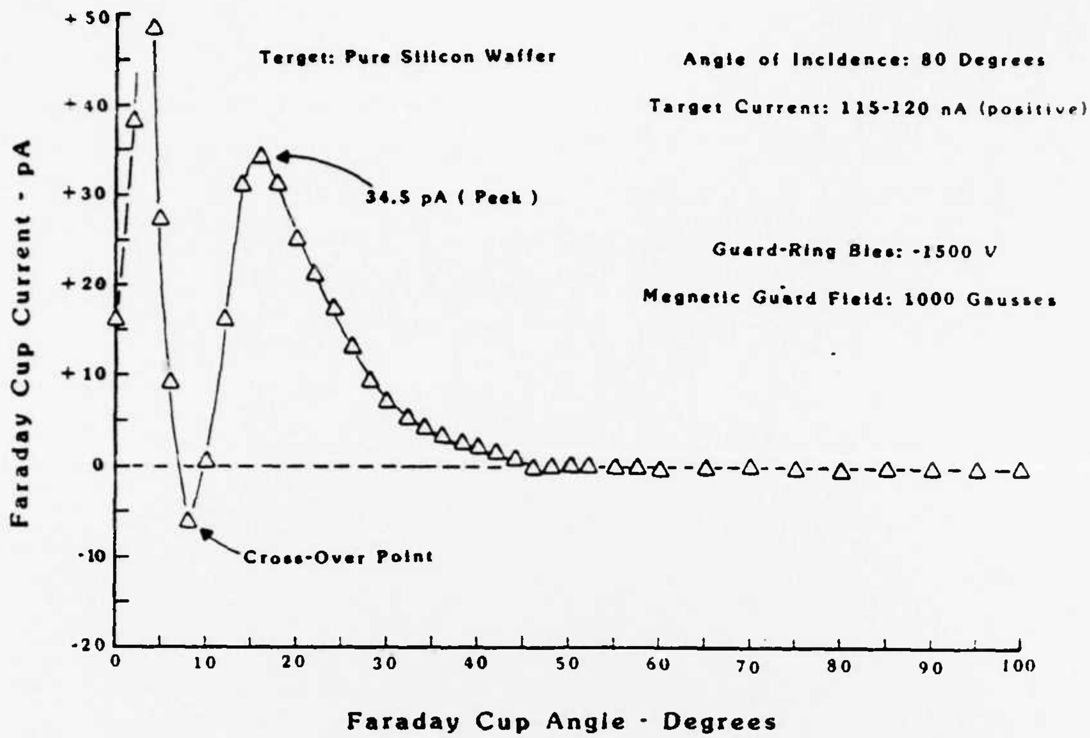


Figure 7. Backscatter protons as a function of 2 MeV protons bombarding a silicon target at 80 deg angles of incidence.

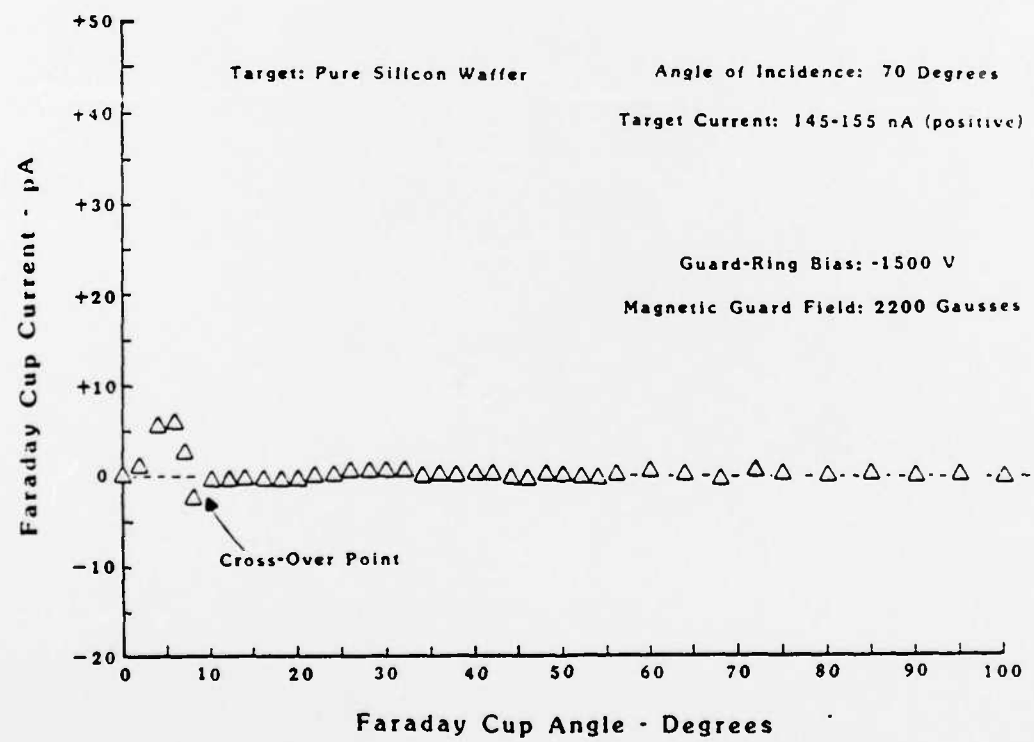


Figure 8. Backscatter protons as a function of 4 MeV protons bombarding a silicon target at 70 deg angle of incidence.

Figure 7 shows the plots of backscattering protons as a function of 2.0 MeV protons bombarding the target at 80 deg. As in the 6.0 MeV and 4.0 MeV irradiation, the peak backscatter current (34.5 pA) occurred at the reflection angle of 6 deg. However, the total backscatter current (and the reflection angles at which it was recorded) was notably larger. At 2.0 MeV, the total measured backscatter current was close to 0.4 percent of the total incident current. Also, the reflection angles of the detectable backscattering particles increased in range from the crossover point to the 45 deg position of the Faraday cup.

The plots in Figs. 5 through 7 also show a substantial number of protons propagating completely through the test samples. These proton transmissions were detected when the angular position of the Faraday cup was between zero and 10 deg (before the crossover point). This was not expected, because the depth of the silicon test wafers was too thick (546 $\mu m$) to allow the 2.0 MeV to 6.0 MeV protons to penetrate completely through the sample. This unexpected occurrence was attributed to a phenomenon called "channeling" (Ref. 7). A more detailed explanation of this mechanism is presented in the discussion section.

The final data plot (Fig. 8) shows the effect of changing the angle of incidence from 80 deg to 70 deg. The results showed that this small change in the angle of incidence reduced the detection of backscatter current to near zero. Also significantly reduced was the number of protons propagating out the back surface of the silicon target.

## 4.0 THEORETICAL RESULTS

Summaries of the theoretical results that can be compared with the four measured plots in Section 3.0 are presented in Figs. 9 through 12. These graphs (determined by the computer program called TRIM) show the calculated backscatter proton count as a function of the angular position of the Faraday cup used in the experimental setup.

Figure 9 shows the theoretical backscatter proton count as a function of 6.0 MeV protons striking a silicon target at an 80 deg angle of incidence. The plot shows that for 100,501 protons hitting the target, 257 protons (≈0.25 percent of the total incident number) were scattering out of the sample. The actual calculations showed that most of the backscattering occurred, with respect to the plane of the test sample, at angles of reflection between zero and 20 deg. This would correspond to 10 to 30 deg on the experimental Faraday cup measurement. Also (but not shown), the calculated energies of these backscattering protons ranged from 6.0 MeV down to 66.7 KeV, with the higher energy protons scattering out near the Faraday cup's crossover point.

The calculated backscatter protons as a function of 4.0 MeV protons bombarding the silicon target at an 80 deg angle of incidence are presented in Fig. 10. In this graph, the backscatter number is 305 which is ≈0.30 percent of the 100,503 incident particles. Most of these scattering protons are also shown to occur between zero and 20 deg angle of reflection (10 to 30 deg on the Faraday cup setup), with energies ranging from 4.0 MeV to 44.4 KeV. Again, the higher energies will occur near the setup's crossover point.

Figure 11 presents the calculated backscatter count for 2.0 MeV protons hitting the silicon at an 80 deg angle of incidence. Under these conditions, the theoretical backscatter count increased to 443 or ≈0.44 percent of the total incoming number. In addition, the spread in the angles of reflection increased from zero to ≈37 deg, with the maximum number still occurring between zero and 10 deg. The energies of the backscattering protons ranged from 2.0 MeV to 22.2 MeV.

The effects of changing the angle of incidence of the bombarding protons from 80 deg to 70 deg is presented in Fig. 12. Illustrated is the calculated backscatter proton count resulting from 4.0 MeV protons striking a silicon

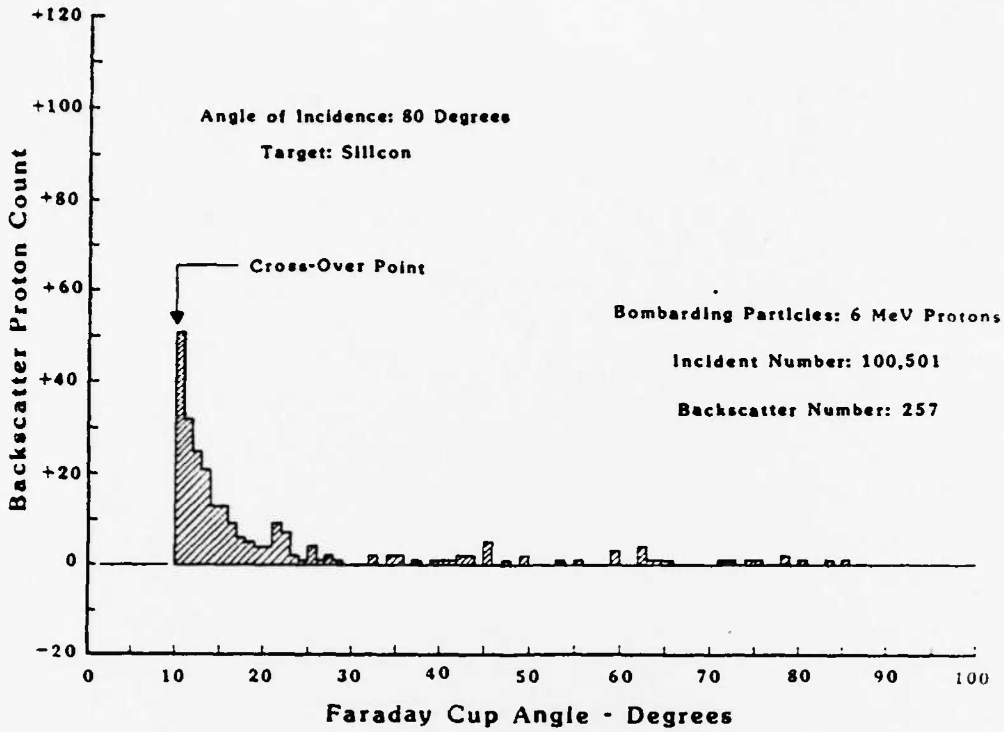


Figure 9. Theoretical calculations of backscatter protons as a function of 6 MeV protons bombarding a silicon target at 80 deg angle of incidence.

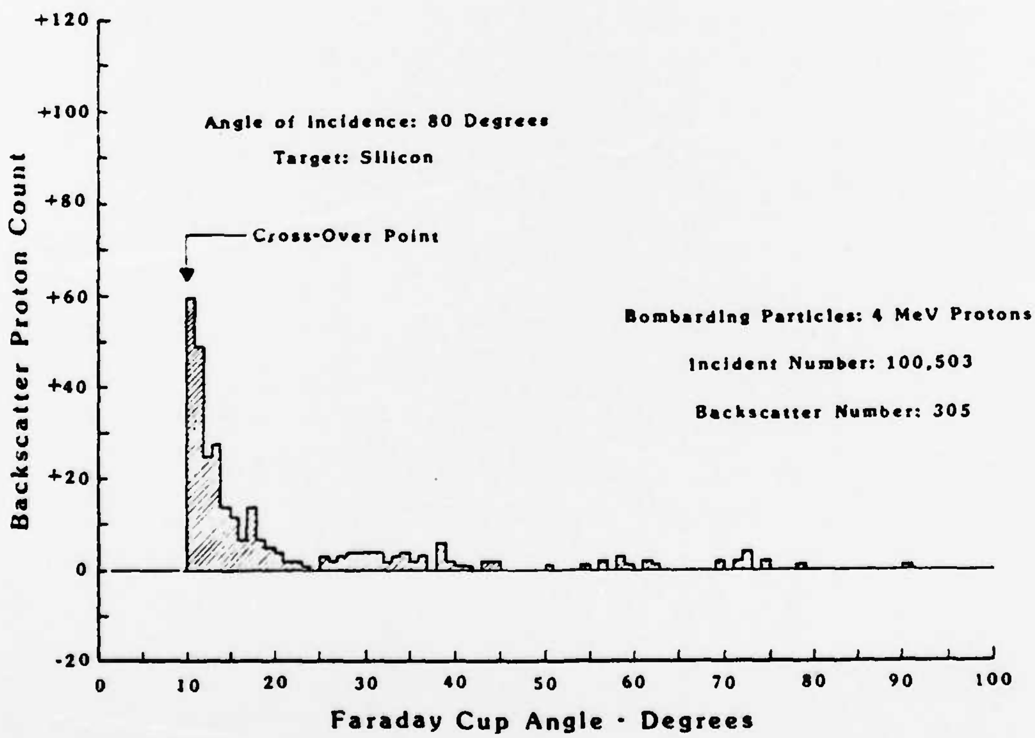


Figure 10. Theoretical calculations of backscatter protons as a function of 4 MeV protons bombarding a silicon target at 80 deg angle of incidence.

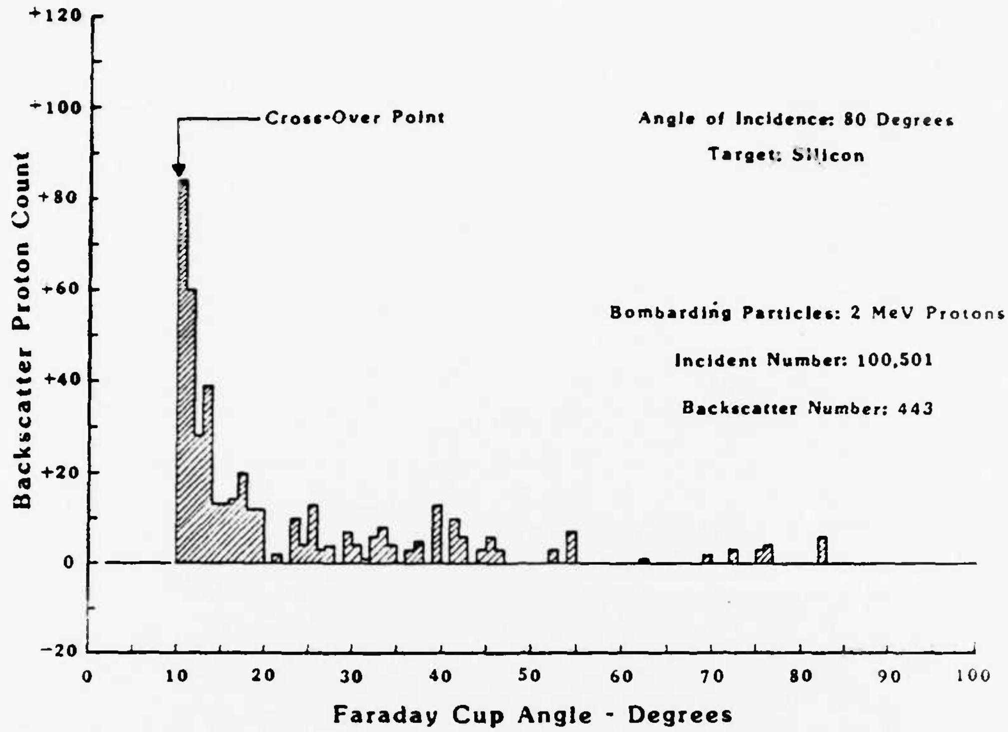


Figure 11. Theoretical calculations of backscatter protons as a function of 2 MeV protons bombarding a silicon target at 80 deg angle of incidence.

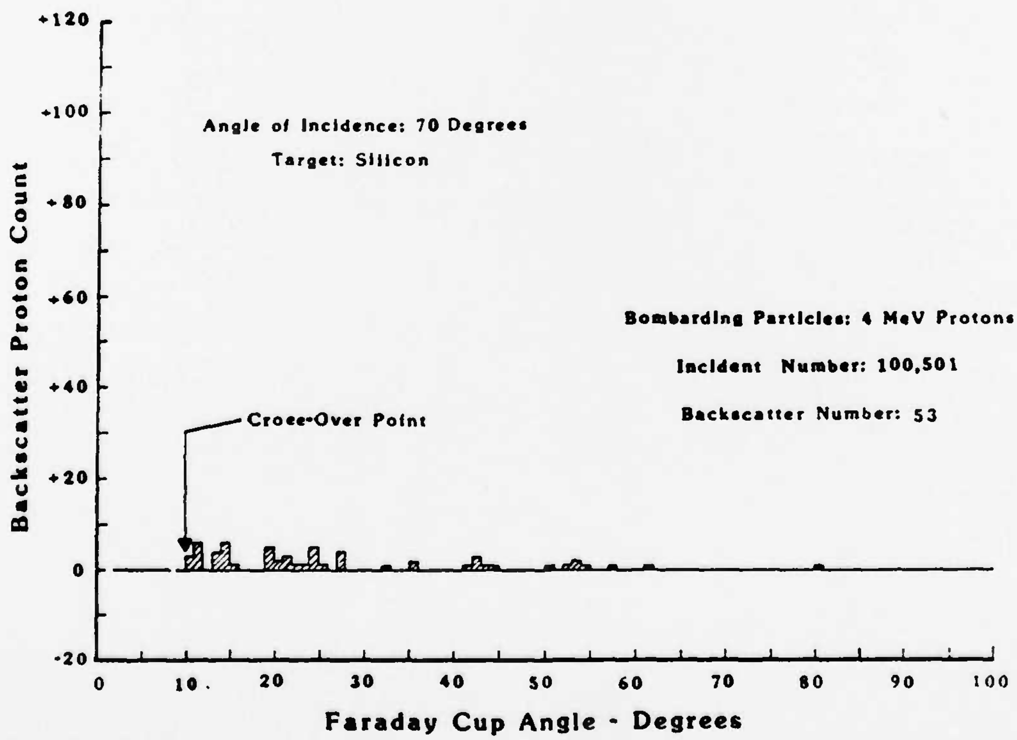


Figure 12. Theoretical calculations of backscatter protons as a function of 4 MeV protons bombarding a silicon target at 70 deg angle of incidence.

target at 70 deg angle of incidence. Again, the backscatter count is plotted as a function of the angle position of the Faraday cup used in the test setup. The results show, with a 10 deg decrease in the incident angle, the backscatter count decreased to 53 (compared to 305 at 80 degrees incidence in Fig. 10). This reduced scatter count is only ≈0.05 percent of the total 100,501 incident number. The calculated backscatter energies were the same as the data presented in Fig. 10.

The final two plots (Figs. 13 and 14) show the theoretical backscatter count for 500 KeV and 100 KeV protons bombarding a silicon target at an 80 deg angle of incidence. Note that, due to the energy and beam current limitations in the LANL proton accelerator, the data in these two graphs could not be collaborated with experimental results.

Figure 13 presents the results for 500 KeV protons. The theoretical backscatter count is 945 which is 0.94 percent of the total incident number. Also showing an increase (over the full measuring range of the Faraday cup), is the spread in the angles of reflection. Backscatter proton energies were calculated to be 500 KeV to 5.6 KeV, with the particle energy increasing as the Faraday cup got closer to the experimental crossover point. Note that all the 106 backscatter protons occurring between 10 and 11 deg on the Faraday cup angle have the highest energy of 500 KeV.

The final plot (Fig. 14) shows the theoretical count for 100 KeV bombarding protons. At this reduced energy, the predicted backscatter proton count increased significantly (over the full measuring range) to 11,714. This number translates to 11.66 percent of the 100,501 incident number. The calculated backscatter energies ranged from 100 KeV at the crossover point to 1.1 KeV at the 99 deg measuring mark.

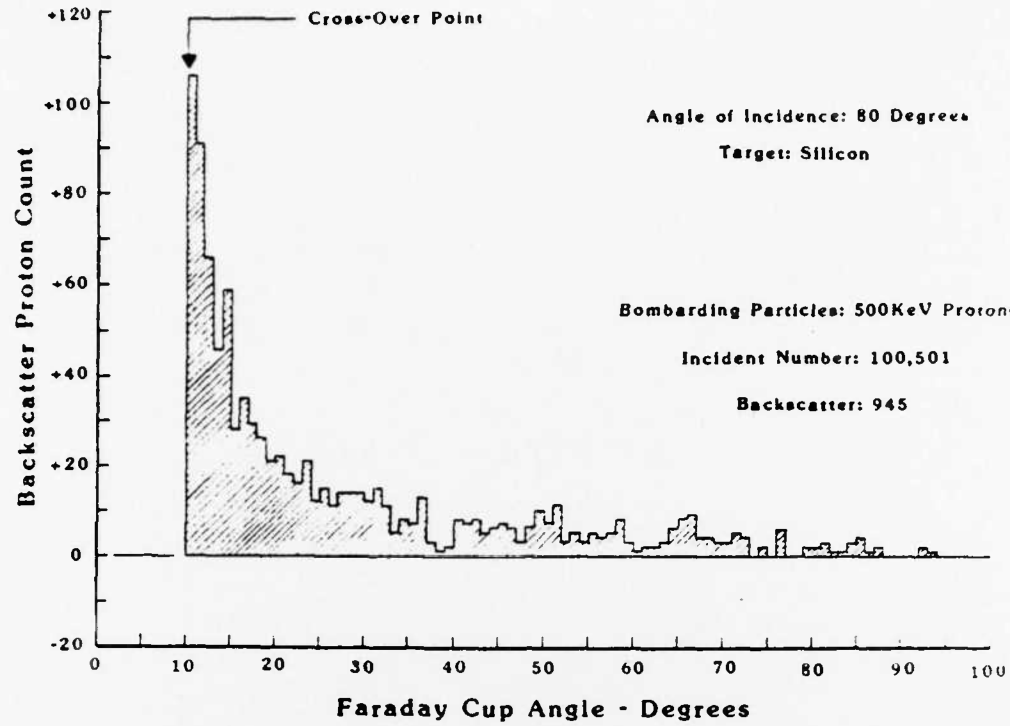


Figure 13. Theoretical calculations of backscatter protons as a function of 500 KeV protons bombarding a silicon target at 80 deg angle of incidence.

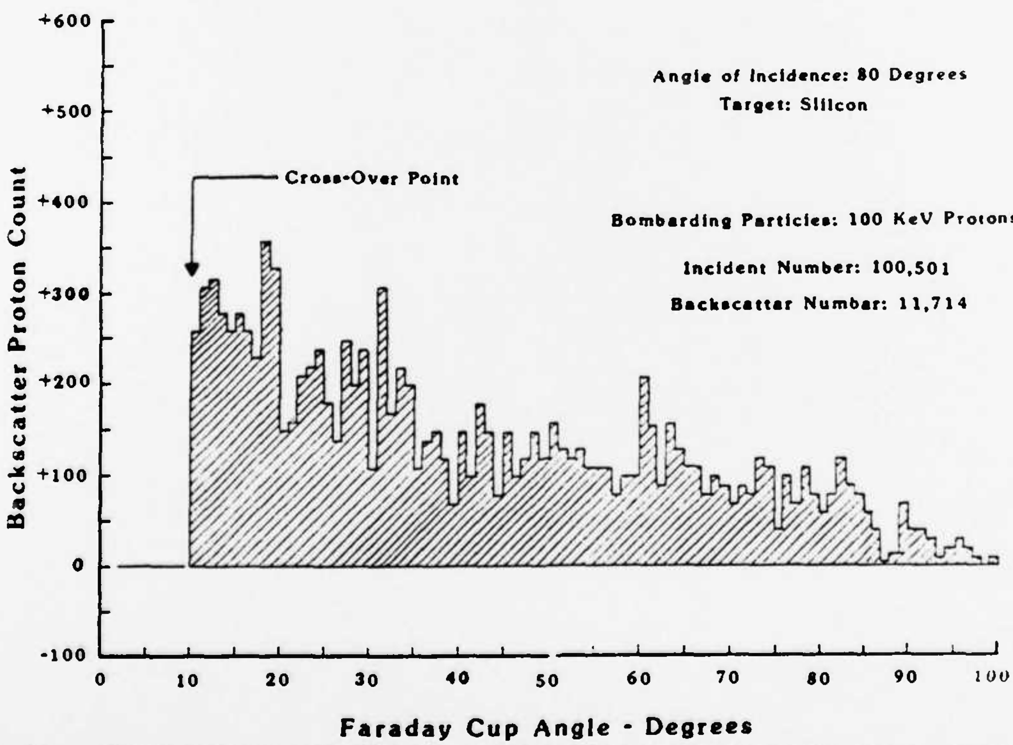


Figure 14. Theoretical calculations of backscatter protons as a function of 100 KeV protons bombarding a silicon target at 80 deg angle of incidence.

## 5.0 DISCUSSION

The experimental and theoretical results presented in this report are meaningful because they answer the question set forth in the objective. That is: does proton backscattering become significant (>10 percent) when high energy protons, 6 MeV and below, strike silicon targets at incident angles >65 deg? The answer was no for proton energies at 500 KeV and greater, and yes for proton energies at 100 KeV and lower. For proton energies between 100 KeV and 500 KeV, the answer was maybe.

For 80 deg incident protons, with energies of 500 KeV and above, the maximum proton backscatter percentage never reached 1 percent of the incident number. In fact, as the incident proton energies went up, the backscatter percentage count went down. This finding lead to the determination that backscattering protons, generated from incident protons of 500 KeV and higher, would have little effect in altering the radiation induced proton damage in silicon electronics. This would be true for all impinging protons with incident angles $\leq$80 deg.

However, the theoretical calculations showed (Fig. 14), as the incident proton energies decreased into the range of 100 KeV, that the effects of backscattering protons would become important. As an example, for 100 KeV protons impinging upon the target at an 80 deg angle of incidence, the backscatter count would approach 12 percent of the incident number. At this level, the backscatter protons would become a factor in determining the proton induced damage within a silicon device. The reason is that only 88 percent of the incident protons would be travelling deep enough into the target to cause radiation damage. On the other hand, because of little penetration, the 12 percent backscattering protons would not produce any measurable damage. The outcome would be a lower radiation damage than predicted.

The impact of incident protons with energies between 500 KeV and 100 KeV will be dependent upon the silicon device under irradiation. Note that (in this energy range) the maximum proton backscatter number will scale from 1 percent at 500 KeV to 12 percent at 100 KeV. If the silicon device that is being irradiated is a sensitive detector, then a 1 percent backscatter count could be important. On the other hand, if the silicon sample is a radiation "hardened" device, then a backscatter proton count up to 10 percent might not be important.

The results were also significant because they showed good agreement between the measured and the calculated data. This excellent similarity added legitimacy to both approaches. The theoretical plots, however, showed a slightly higher percentage in the backscatter counts than the measured results. This was expected because the experimental measurements were limited to the two-dimensional viewing plane of the Faraday cup. The theoretical findings took into account the three-dimensional plane. As a result, the calculated backscatter counts would always be larger.

Another noteworthy event, observed during the experimental measurements, was the recording of what appeared to be proton emissions out of the back surface of the test samples (Figs 5 through 7). This was unexpected, since the thickness of the silicon targets was 546 $\mu$m. At this thickness, the 2.0 MeV to 6.0 MeV protons should not have travelled completely through the wafer. A proton with an energy of at least 8.5 MeV would be needed to penetrate completely through the sample (Ref. 8).

A satisfactory explanation for this proton emission is a phenomenon called channeling. Channeling will occur in the crystalline silicon wafer when the incoming protons are directed along the major crystal axis of the test sample. When this happens, the energetic charged particles are steered by the atomic rows of the sample solid, thereby allowing greater penetration depth, without any interactions. The result would be a mean range greater (possibly several times) than that of a randomly directed particle. A possible result (as in this case) would be protons of lower than expected energies travelling completely through the wafer.

This explanation was reinforced with the data presented in Fig. 8. In this plot, the data show that for a small change in the incident angle (from 80 deg to 70 deg), the protons passing through the sample were significantly reduced. This implies that the crystal axis of the test wafers and the path of the bombarding protons were no longer in alignment. A result of such a misalignment would be a greater number of interactions between the incoming charged particles and the atoms within the silicon target. Increasing these interactions would result in a greater rate of energy loss and a reduction in the mean range of the charged particles within the material. The outcome would be less proton propagating through the test sample.

Finally, a clarification on the past data (Fig. 2) which generated the interest in this backscatter study is now needed. The data in this report eliminated the concept that backscattering protons were the cause of the unpredicted drop in the damage sensitivity of the 80 deg proton irradiations. As a result, additional studies were later made, and the true cause was determined to be an internal mechanism (Ref. 4). That is, the drop in the damage rate from the 80 deg incident protons (12 MeV and lower) was attributed to a large buildup of trapped charges (generated by the incoming protons) in the gate structure of the test devices. This charge buildup, which was proportional to the incident angle of the incoming protons and inversely proportional to their energies, was accelerated when the angle of the incident particles approached 80 deg. The result was a rapid creation of an internal electrical field which countered the applied gate field during the irradiations. The net effect was a steady decrease in the overall electric field across the gate oxides of the test devices. Since the radiation damage in MOS electronics is proportional to the magnitude of the gate oxide field, any reduction in this field (during a radiation) would also result in a drop in the damage. This was true for the data in Fig. 2.

# 6.0 CONCLUSION

From the data collected in this work, the following conclusions were formulated.

a. The major backscattering particles from high energy protons bombarding solid-state (silicon) electronics were energetic electrons. The energy and number of scattering electrons were directly proportional to the energy of the incoming protons, the incident angle of the protons, and the number of impinging protons.

b. For incident protons (on silicon) with energies of 500 KeV and above, backscattering protons will equal <1 percent of the total number striking the target. At this low percentage number, backscatter protons will have little effect in altering the radiation induced proton damage in silicon electronics. This will be true for all bombarding protons with incident angles ≤80 deg.

c. The number of backscattering protons will get larger as the energy of the striking protons goes down and as the angle of incidence of the incoming particles increases. When the angle of incidence of the bombarding protons approaches 80 deg, and their energies drop to ≈100 KeV, the backscatter proton count, in silicon, will reach close to 12 percent of the incident number. At this level, the backscatter protons will have a measurable effect (a reduction) on the induced proton damage within silicon electrons.

d. The backscatter proton count, their energies, and angles of reflections (in silicon and other solids) can accurately be calculated by a computer program called TRIM.

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